PROCEEDINGS OF SCIENCE

First Year of Stellar-Mass Black Hole Observations with the Imaging X-ray Polarimetry Explorer

Nicole Rodriguez Cavero* **on behalf of the *IXPE* accreting stellar-mass black hole topical working group**

Physics Department, McDonnell Center for the Space Sciences, and Center for Quantum Leaps, Washington University in St. Louis, St. Louis, MO 63130, USA

E-mail: n.rodriguez@wustl.edu

The Imaging X-ray Polarimetry Explorer (*IXPE*), launched on December 9, 2021, enables X-ray polarimetric observations with unprecedented sensitivity in the 2-8 keV energy range. X-ray polarization allows us to test the processes in accretion disks and coronae of stellar-mass black holes in X-ray binaries found in both soft and hard spectral states. Every state is characterized by a combination of thermal disk, coronal, or reflected emission—each type containing different information about the environment around the black hole that can be understood through polarization. In 2022, *IXPE* measured the polarization signatures of four stellar-mass black holes: Cygnus X-1, 4U 1630-47, Cygnus X-3, and LMC X-1. We report on the physical consequences of these first *IXPE* observations and the science driven by this new chapter in X-ray polarimetry.

Multifrequency Behaviour of High Energy Cosmic Sources XIV (MULTIF2023)
12-17 June 2023
Palermo, Italy

*Speaker

https://pos.sissa.it/

PoS(MULTIF2023)039

1. Introduction

Black hole X-ray binaries (BHXRBs) consist of a stellar-mass black hole in orbit with a donor star. The matter transferred from the donor star to the accretor gives rise to structures like the black hole accretion disk, corona, and radio jet. To study these components, we turn to X-ray polarization. Polarimetry offers a unique geometrical insight into BHXRBs from which we can rectify the degeneracies between the black hole mass, spin, and inclination, constrain the shape of their coronae, and predict the origin of soft X-ray seed photons.

In the standard Shakura-Sunyaev approach, the structure of the accretion flow is driven by the conversion of gravitational potential to heat via viscous stresses [1]. The accreted matter from the companion star forms an optically thick disk around the black hole which emits at a quasi-blackbody temperature of $T(r) \sim r^{-3/4}$ producing a geometrically thin disk so long as the luminosities are well below Eddington [2]. Around the inner accretion flow we also find the corona: a structure of geometrically thick, optically thin $\sim$ 100 keV plasma that radiates in the form of Comptonized, bremsstrahlung, and/or synchrotron emission [2, 3]. Up until recent, several corona geometries and locations were proposed but unconstrained. The most common ones include the cone-shaped coronae in the funnel regions around the black hole spin axis, the sandwich or wedge-shaped coronae extended in the plane of the disk [4], the lamp-post coronae consisting of a spherical or conical body of plasma located on the black hole rotation axis and at some height above and below the disk [5], and the hot inner flow-truncated disk coronae in which the inner disk region is replaced with a region of hot plasma possibly through evaporation of the disk [6].

BHXRBs can be found in different states of accretion typically defined by either their luminosity, power-law photon index, or the absence/presence of a jet [7]. Their spectra has contributions from thermal, Comptonized, and reflected emission. In the high/soft state (HSS), also known as the thermal-dominant state, the total emission is dominated by thermal radiation from the accretion disk that peaks at around $\sim$ 1 keV. We typically employ a multi-temperature blackbody model to explain the majority of the observed soft X-ray energy spectra [8]. In the low/hard state (LHS), most of the X-ray emission comes from Compton scattering in the coronal plasma peaking at $\sim$ 100 keV. During this state, the BHXRB energy spectra are dominated by a power-law component in the 5—20 keV energy range with a photon index $\propto E^{-\Gamma}$ of $1.5 < \Gamma < 2$ [2]. Additionally, during the LHS, the total emission is also comprised of reflected emission from photons Comptonized in the corona bouncing off the disk giving rise to fluorescent emission lines [9]. The LHS is also associated with the presence of a steady jet detected at radio frequencies [7]. In the case of Cygnus X-3, however, the hard state is associated with radio quiescence [10] and exhibits a hard X-ray spectrum peaking at $\sim$ 20 keV [11]. Stellar-mass black holes can also be found in the steep power-law state (SPL) characterized by comparable contributions of thermal and power-law components—the latter with a steep photon index of $\Gamma \sim 2.5$ [12].

The polarization signature of accreting stellar-mass black holes will vary depending on the state in which they are observed since the relative contribution to the emission from different components of the black hole system will affect the direction of polarization. Numerical general relativistic ray-tracing and radiation transport codes [4, 13–15] use Chandrasekhar's results for the polarization of emission from a fully ionized atmosphere [16] to predict the X-ray polarization of accreting stellar-mass black holes. In the thermal state, the expected polarization of the thermal disk emission is 0.1%, 0.7%, and 2.3% for $i = 20°$, 40°, and 60°, respectively [16]. However, measured PDs can differ from Chandrasekhar's predictions owing to general relativistic effects. Rotation of the polarization vector due to parallel transport along curved trajectories around the black hole has a depolarizing effect on the signal [17]. Moreover, while direct thermal emission is expected to be polarized parallel to the accretion disk, returning radiation to the disk surface and reflected towards the observer is polarized in the direction of the black hole spin axis and presents a higher PD [13]. Polarization observations of sources in the HSS allow us to test the standard thin disk model of accretion as well as constrain black hole spin and inclination by analyzing the dependence of polarization with respect to energy [13, 18]. Since coronal emission is expected to be polarized perpendicular to the direction of the scattering surface [4], polarization measurements in the LHS can be used to determine the properties of the coronal plasma as well as the inner accretion flow.

The Imaging X-ray Polarimetry Explorer (*IXPE*, [19]) is a collaboration between NASA and the Italian Space Agency. *IXPE* is the first X-ray polarization space observatory since the eight Orbiting Solar Observatory (*OSO-8* [20]) and it is 30 times more sensitive for a 10 mCrab source [21]. The instrument is comprised of three gas pixel detector (GPD) units, each paired with a focusing grazing incidence mirror at a 4 meter focal length [22]. The GPD provides a 1-2 μs timing accuracy and an angular resolution of $\leq$ 30 arc-seconds [21]. *IXPE* grants simultaneous timing, imaging, spectral, and polarimetric measurements in the 2-8 keV energy band—making it a powerful tool to study astrophysical sources. In 2022, *IXPE* observed four stellar-mass black holes located in X-ray binaries. The highly accurate polarization measurements of these observations have yielded impressive results thus far. In the following, we discuss the four *IXPE* stellar-mass black hole observations that took place in 2022 and their implications on the structure of the black hole system and its emission mechanisms.

2. Results

The first year of *IXPE* observations of BHXRBs revealed higher-than-expected linear polarization degrees (PDs) that increased with energy and polarization angles (PAs) that remained relatively constant in the 2-8 keV energy band. These high precision measurements were accompanied by quasi-simultaneous observations from other X-ray instruments: most commonly NICER [23] and *NuSTAR* [24]. Cygnus X-1 and Cygnus X-3 were observed in the hard states where black hole coronal and reflected emission tend to dominate. LMC X-1 and 4U 1630-47, on the other hand, were observed in the soft state where thermal emission from accretion disk dominates the signal. We highlight the results of these observational campaigns.

2.1 Cygnus X-1

Cygnus X-1 is a persistently bright and highly variable $21.2 \pm 2.2 M_\odot$ [25] black hole (although reverberation studies suggest a mass of $16.5 \pm 5 M_\odot$ [26]) located 2.22 kiloparsecs away. It exhibits a radio jet—an outflow of ionized matter organized in two diametrically opposing beams extending along the axis of rotation of the black hole. *IXPE* observed Cyg X-1 between May 15th and 21st of 2022 for a total exposure of $\sim$ 242 ks in the LHS [27]. The Cyg X-1 LHS observation revealed a polarization degree of $4.01 \pm 0.20\%$ at a polarization angle of $-20.7° \pm 1.4°$. Figure 1(a) shows that the measured PA and the radio jet of the source are almost perfectly aligned. This alignment

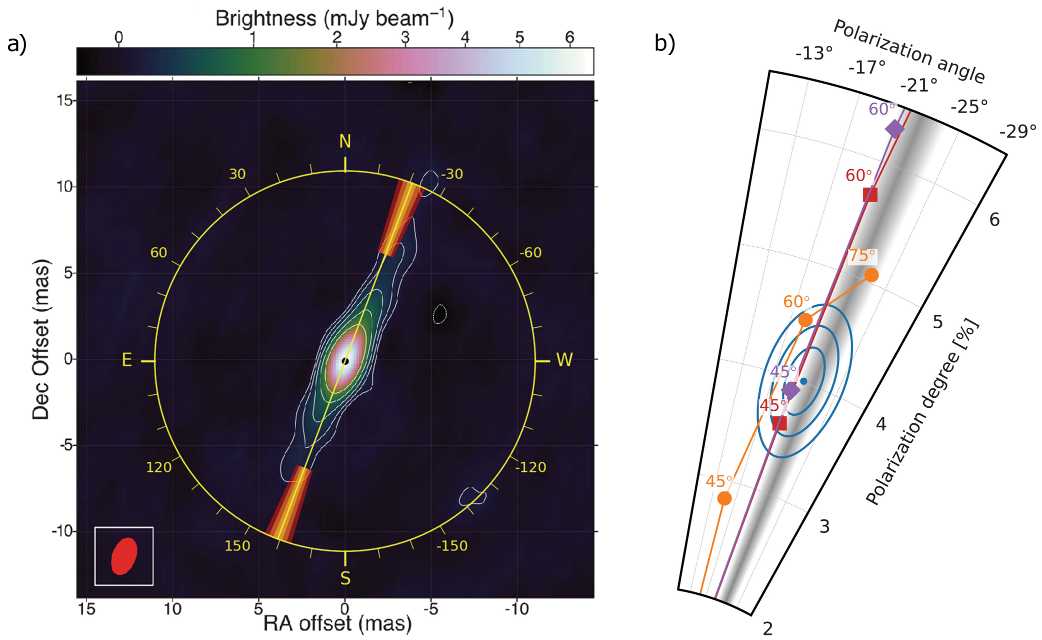

Figure 1: Figures from Krawczynski et al. 2022 [27]. (a) *IXPE* PA of Cygnus X-1 in the 2-8 keV energy band during the LHS observation overlaid on top of the radio jet imaged by the VLBA [25]. Yellow, orange, and red bands give the PA at the 68%, 95% and 99.7% confidence levels. (b) Comparison of the measured PD and PA (blue) with simulated polarization results for different corona configurations: sandwich coronae (orange) and hot inner flow–truncated disk corona with disk seed photons (red) or synchrotron seed photons (purple). Blue ellipses represent measurements to the 68%, 95% and 99.7% confidence levels.)

suggests that the X-ray polarization in the *IXPE* energy band, which mainly comes from the inner disk, is also perpendicular to the inner accretion disk plane. Furthermore, it indicates that the inner X-ray emitting region of the black hole system and the radio jet are connected.

Different coronal geometries were tested using the `kerrC` [14] and `MONK` [15] raytracing codes to replicate the observed high PD and correct PA alignment. We found that models in which the corona was vertically extended along the black hole spin axis (such as the cone-shaped and lamp-post coronal models) either predicted polarization degrees significantly below those observed and/or yielded polarization angles perpendicular to the jet axis. On the other hand, coronae extended laterally on the plane of the accretion disk predicted results more in accordance to the observation. The two geometries that were able to reproduce the data were the wedge-shaped/sandwich corona and the hot inner flow-truncated disk corona shown in Figure 1(b). These models were able to explain the high, energy-dependent PD of the observation as well as produce an energy-independent polarization vector perpendicular to the accretion disk plane or parallel to the radio jet, albeit with higher inclinations than that of the orbital plane. This mismatch between inclinations could be explained by a misaligned spin axis. Alternatively, lower inclinations can be obtained when the laterally extended corona is outflowing as shown in Poutanen et al. 2023 [28].

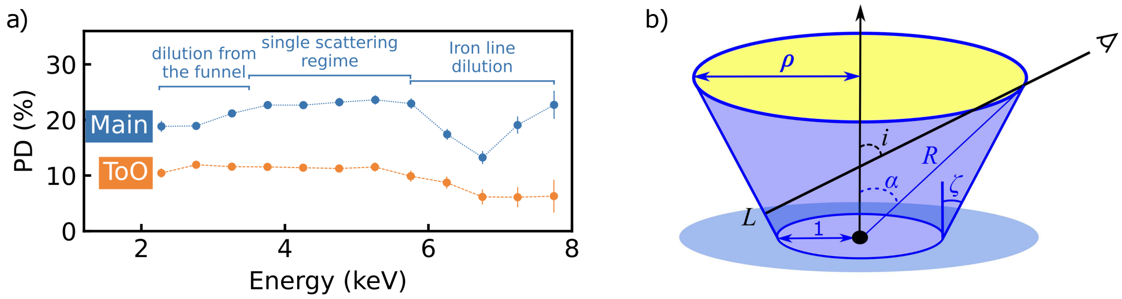

Figure 2: Figures from Veledina et al. 2023 [32]. (a) *IXPE* PD vs energy of Cygnus X-3 in the 2-8 keV energy band during the LHS observation (Main, blue) and the intermediate, softer observation (ToO, orange). Error bars are given to 1σ. (b) Schematic showing the proposed geometry of the collimating funnel region obscuring the primary source. An observer at inclination i will see the reflection from the inner surface of the funnel until point L. ζ is the half-opening angle of the funnel, R is the distance to the X-ray photosphere, and α is the angle at which the upper boundary of the funnel is seen from the primary X-ray source.

2.2 Cygnus X-3

Cygnus X-3 is a persistent black hole candidate at about 9.7 kiloparsecs from us [29]. It is located in a binary with a Wolf-Rayet star and it is the brightest radio source among X-ray binaries [30, 31]. From October 14th to October 19th and from October 31st to November 6th of 2022, *IXPE* observed Cyg X-3 for $\sim$ 538 ks and measured a PD of $20.6 \pm 0.3\%$ at a PA of $90.1° \pm 0.4°$ [32]. This main observation occurred while the source was in the hard X-ray, radio quiescent state. A second observational campaign for the source was later conducted from December 25th to December 29th, 2022 for $\sim$ 199 ks as the source transitioned to a softer state. For this Target of Opportunity (ToO) observation, *IXPE* measured a PD of $10.0 \pm 0.5\%$ at a PA of $90.6° \pm 1.2°$ [32]. The PA in both observations was orthogonal to discrete radio ejections reported for the source suggesting that the polarization vector is approximately aligned with the plane of the accretion disk. Figure 2(a) shows that the PDs for both observations and their negligible energy dependence. In fact, the PD only decreases at around 6.4 keV where we expect the Fe Kα emission line to depolarize the signal [33]. The very high PD of the hard state observation and its orientation suggested that the observed emission was comprised mostly from reflected emission.

Correspondingly, Veledina et al. 2023 [32] posited that an optically thick medium shaped as a funnel must be collimating the radiation emitted by the accretion disk along its walls. Figure 2(b) shows the proposed funnel region. The $\sim$ 10% change in polarization during the ToO observation when the source softened can then be explained as the outflow becoming more transparent. Given this geometry, the observed PD corresponds to a scattering angle of $\sim$ 38° for which the model constrains the half-opening angle to $\alpha \lesssim 15°$. Under these conditions, the apparent luminosity for an observer looking down at point L in the funnel was estimated to be $L \gtrsim 5.5 \times 10^{39}$ erg s^{-1} which would make Cyg X-3 an obscured galactic ultraluminous X-ray source.

2.3 LMC X-1

LMC X-1 is an extragalactic $10.91 \pm 1.41 M_\odot$ [34] black hole located 50 kiloparsecs away in the Large Magellanic Cloud [35]. The source accretes matter from a $31.8 \pm 3.5 M_\odot$ early-type

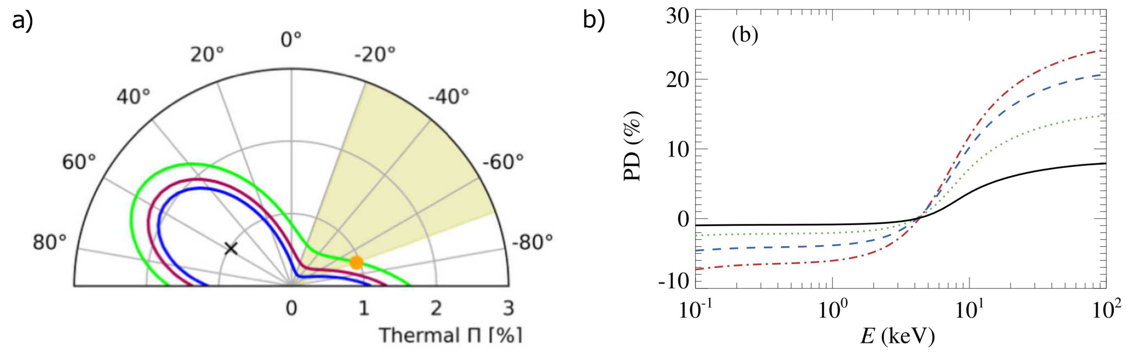

Figure 3: Figures from Podgorný et al. 2023 [37]. (a) Contour plot of the LMC X-1 PD and PA of the thermal disk component when the PD of the coronal component is set to 0% and their relative PAs are forced to be perpendicular. The blue, red, and green lines indicate 68%, 90% and 99% confidence regions, respectively. The orange dot represents the 3σ upper limits of the thermal emission polarization degree if we assume it is polarized in the direction of the projected accretion disk plane (yellow). (b) PD predicted by the slab corona model of 10 keV electron temperature and $\tau_T = 1.26$ Thomson optical depth. Positive/Negative PD values correspond to a PA direction perpendicular/parallel to the disk.The black solid, green dotted, blue dashed, and red dot-dashed lines represent inclinations of $i = 30°$, $45°$, $60°$, and $75°$, respectively.

star making the system a high-mass X-ray binary [34, 36]. *IXPE* observed LMC X-1 between October 19th and October 28th, 2022 for a total of ~ 562 ks [37]. The observation took place while the source was in the HSS. The measured polarization was below the minimum detectable polarization of 1.1% at the 99% confidence level for the 2-8 keV polarization so only an upper limit was imposed. The measured PD was 1.0 ± 0.4% yielding a 3σ upper limit of 2.2% while the PA suggested alignment with the projected ionization cone. Podgorný et al. 2023 [37] analyzed quasi-simultaneous NICER and *NuSTAR* data to decompose the total *IXPE* spectra into thermal disk and coronal emission contributions. In order to investigate how the thermal component was polarized, the polarization of the Comptonized component was set to 0%, 4%, and 10% and the PAs of both components were forced to be perpendicular to each other. Figure 3(a) shows the contour plot for one of the configurations where the polarization of the coronal emission is 0%. In this instance, the thermal emission PD upper limit at the 99% confidence level is 2.2% and 1.0% if we require this component to be polarized in the direction of the accretion disk. When the PD of the coronal component is set to 4% and 10%, the PD of the thermal component if oriented in the plane of the disk reduces to 0.9%.

Podgorný et al. 2023 [37] also employed a slab coronal geometry to understand the effect of the relative contributions of the thermal disk and coronal emissions to the total PD. Figure 3(b) shows that at ~ 5 keV, the change from negative to positive PD (which corresponds to a change of total polarization direction from parallel to perpendicular to the disk) occurs in the *IXPE* 2-8 keV band. As expected, competing components of parallel and perpendicular polarization tend to depolarize the radiation emitted from the innermost regions of the disk [13, (see Fig. 4)] and this could explain the overall low polarization signal from the source.

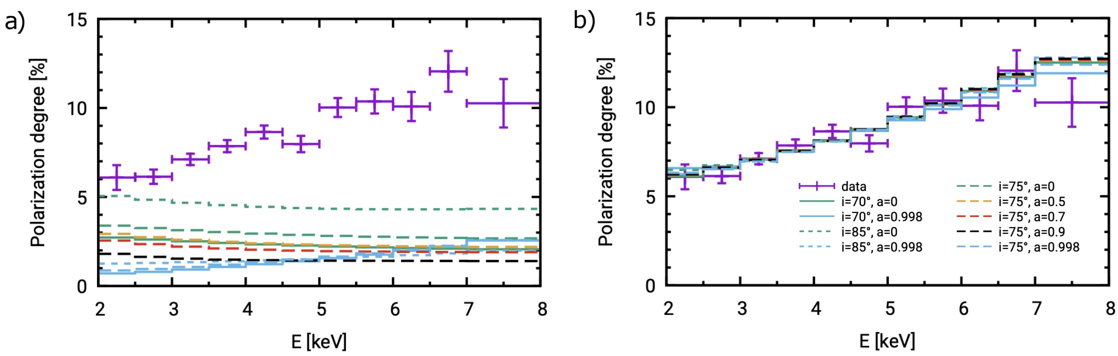

Figure 4: Figure 8 from Ratheesh et al. 2023 [42]. 4U 1630-47 *IXPE* PD (purple) at the 68% confidence level and model predictions. Solid, dashed, and dotted lines represent inclinations of 70°, 75°, and 85°, respectively; green, yellow, red, black, and light blue colors represent spins of 0, 0.5, 0.7, 0.9 and 0.998, respectively. (a) PD predictions of a standard Novikov-Thorne thin disk with Chandrasekhar's pure electron-scattering atmosphere. (b) PD predictions for a thin disk with an outflowing, partially-ionized atmosphere of optical thickness $\tau = 7$ and velocity $v \sim 0.5c$.

2.4 4U 1630-47

4U 1630-47 is an X-ray transient source with outbursts every ~ 600 days [38, 39]. It is located about 4.7-11.5 kiloparsecs away [40] and its parameters remain largely unconstrained due to extinction in the line of sight [41]. The first *IXPE* observation of 4U 1630-47 was from August 23rd to September 2nd, 2022 for a total exposure time of ~ 460 ks. *IXPE* caught the source in the HSS and measured a PD of 8.32 ± 0.17% at a PA of 17.8° ± 0.6° [42]. Spectral fitting of quasi-simultaneous NICER data revealed that the thermal contribution to the total emission was about 97%. The PD linearly increased with energy from 6% at 2 keV to 10% at 8 keV while the PA showed no appreciable energy dependence. The measured PD was considerably higher than the prediction for a pure electron-scattering atmosphere at the estimated 65° inclination of the source—which should place the PD at around 3% [16]. Figure 4(a) shows that the PD of the standard thin disk model under-predicts the observed PD. Since the high rise of the PD with energy could not be explained by the standard thin disk model alone, Ratheesh et al. 2023 [42] propose a thin disk surrounded by a partially-ionized, outflowing atmosphere.

In this model, the partial ionization of the disk atmosphere increases the PD as absorption processes lead to an increased number of photons travelling perpendicular to the disk plane [43]. Additionally, assuming a vertical outflow velocity requires a higher local emission angle to reach the same observer at a fixed inclination due to aberration effects—also resulting in a higher PD. Figure 4(b) shows the PDs predicted for this model for partially-ionized atmosphere of optical thickness $\tau = 7$ outflowing at a $v \sim 0.5c$. This model predicts a PA parallel to the disk, although the lack of information on the source's jet orientation makes it currently impossible to verify this result.

A second *IXPE* observation of 4U 1630-47 occurred after MAXI reported a significant increase in flux hinting that the source was in the SPL state. *IXPE* observed the source from March 10th to March 14th, 2023 for ~ 140 ks and measured a PD of 6.8 ± 0.2% at a PA of 21.3° ± 0.9° [44]. The thermal contributions of the source reported in this state were between 8% and 54% depending

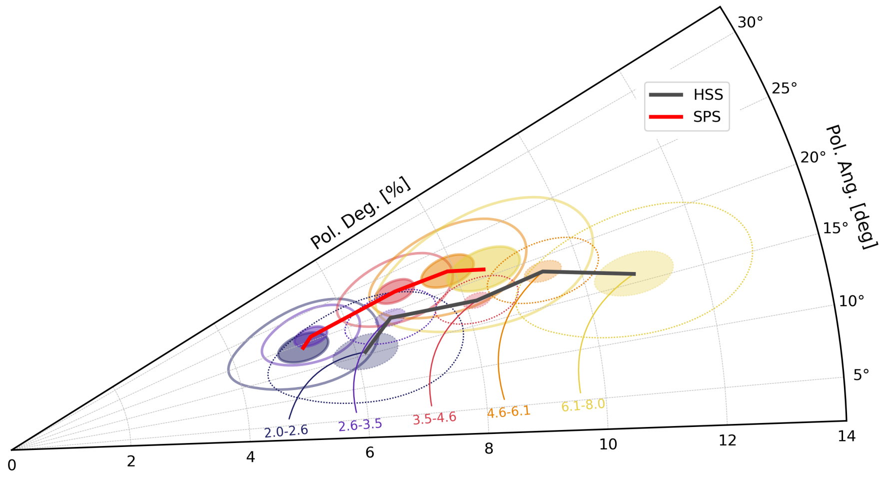

Figure 5: Figure 3 of Rodriguez Cavero et al. 2023 [44]. PD and PA of 4U 1630-47 in the HSS (black) and SPL (red) states binned in 5 logarithmic energy bins. The shaded and unshaded ellipses are confidence contours a the 68.3% and 99.7% confidence levels.

on the spectral models used to fit NICER and *NuSTAR* data acquired during the *IXPE* observation, while the rest of the emission is attributed to a steep power-law component. The polarization results for both *IXPE* observations of 4U 1630-47 are shown in Figure 5. The small 1.5% change in the PD and the constant PA (within 3σ) during the state transition from the HSS to the SPL state were unexpected. The authors attribute these results to an instantaneous increase in electron temperature leading to a change from Thomson scattering processes in the partially-ionized accretion disk atmosphere to inverse Compton scattering that leads to the observed power-law component.

3. Discussion and Conclusions

The first year of *IXPE* stellar-mass black hole observations demonstrated that polarization measurements are crucial to explore the complex environment surrounding these astrophysical sources. In 2022, *IXPE* observed four sources: Cyg X-1, Cyg X-3, LMC X-1, and 4U 1630-47. While the first two sources were observed in the hard spectral states, their polarization properties show vastly different emission geometries. In the case of Cyg X-1, we saw predominantly coronal emission and an energy-dependent PD that allowed us to constrain the corona geometry to laterally extended in the plane of the disk [27]. For Cyg X-3, polarization results showed that most of the emission came from reflection. Cyg X-3 high PD measurement suggested that the disk emission is collimated along the walls of an optically thick funnel region and that the black hole candidate might be an obscured ultra-luminous X-ray source [32].

Although we were not able to achieve a statistically significant polarization measurement of LMC X-1, we obtained an upper limit of the total polarization signal [37]. The derived upper limits for the dominant thermal emission were in line with those predicted by Chandrasekhar for a semi-infinite scattering atmosphere [16]. However, like Cyg X-1, the PA of LMC X-1 seems to be aligned to the projected ionization cone structure. This is puzzling since the thermal emission is 94% of the total emission and is expected to be polarized perpendicular to the ionization cone.

4U 1630-47 was also measured in the HSS and its PD was considerably larger than what estimated by the standard thin disk model [42]. In this case, the polarization of 4U 1630-47 required a partially-ionized, optically thick outflowing atmosphere to achieve that higher PD and yielded a PA parallel to the disk. The source was later observed again in the SPL state [44] where the relative consistency of polarization measurements was surprising given the large changes in the spectral components.

IXPE observations of BHXRBs during 2022 revealed high PDs for three out of the four sources and constant PAs. The proposed outflow geometries that deviate from the standard thin disk-corona configuration underscore the need for a more comprehensive investigation of the plasma in the inner accretion flows. Changes in the winds of the system, evolution of the corona during state transitions, and slim disk models are currently being considered. Future *IXPE* observations of stellar-mass black holes will allow us to put further constraints on models of accretion, investigate a larger sample of sources, and probe different accretion modes of X-ray transients through their spectral state evolution.

Acknowledgments

The Imaging X-ray Polarimetry Explorer (IXPE) is a joint US and Italian mission. The US contribution is supported by the National Aeronautics and Space Administration (NASA) and led and managed by its Marshall Space Flight Center (MSFC), with industry partner Ball Aerospace (contract NNM15AA18C). The Italian contribution is supported by the Italian Space Agency (Agenzia Spaziale Italiana, ASI) through contract ASI-OHBI-2022-13-I.0, agreements ASI-INAF-2022-19-HH.0 and ASI-INFN-2017.13-H0, and its Space Science Data Center (SSDC) with agreements ASI-INAF-2022-14-HH.0 and ASI-INFN 2021-43-HH.0, and by the Istituto Nazionale di Astrofisica (INAF) and the Istituto Nazionale di Fisica Nucleare (INFN) in Italy. This research used data products provided by the IXPE Team (MSFC, SSDC, INAF, and INFN) and distributed with additional software tools by the High-Energy Astrophysics Science Archive Research Center (HEASARC), at NASA Goddard Space Flight Center (GSFC).

References

[1] N.I. Shakura and R.A. Sunyaev, *Black holes in binary systems. Observational appearance.*, *Astronomy & Astrophysics* **24** (1973) 337.

[2] C. Done, M. Gierliński and A. Kubota, *Modelling the behaviour of accretion flows in X-ray binaries. Everything you always wanted to know about accretion but were afraid to ask*, *Astronomy & Astrophysics Review* **15** (2007) 1 [0708.0148].

[3] J.E. McClintock and R.A. Remillard, *Black hole binaries*, in *Compact stellar X-ray sources*, vol. 39, pp. 157–213, Cambridge University Press (2006), DOI.

[4] J.D. Schnittman and J.H. Krolik, *X-ray Polarization from Accreting Black Holes: Coronal Emission*, *The Astrophysical Journal* **712** (2010) 908 [0912.0907].

[5] W. Zhang et al., *Investigating the X-ray polarization of lamp-post coronae in BHXRBs*, *Monthly Notices of the Royal Astronomical Society* **515** (2022) 2882 [2207.03228].

[6] M. Gilfanov, *X-Ray Emission from Black-Hole Binaries*, in *Lecture Notes in Physics, Berlin Springer Verlag*, T. Belloni, ed., vol. 794, p. 17 (2010), DOI.

[7] R.P. Fender, T.M. Belloni and E. Gallo, *Towards a unified model for black hole X-ray binary jets*, *Monthly Notices of the Royal Astronomical Society* **355** (2004) 1105 [astro-ph/0409360].

[8] K. Mitsuda, H. Inoue, K. Koyama, K. Makishima, M. Matsuoka, Y. Ogawara et al., *Energy spectra of low-mass binary X-ray sources observed from Tenma.*, *Publications of the Astronomical Society of Japan* **36** (1984) 741.

[9] J.A. Tomsick et al., *The Reflection Component from Cygnus X-1 in the Soft State Measured by NuSTAR and Suzaku*, *The Astrophysical Journal* **780** (2014) 78 [1310.3830].

[10] A. Szostek, A.A. Zdziarski and M.L. McCollough, *A classification of the X-ray and radio states of Cyg X-3 and their long-term correlations*, *Monthly Notices of the Royal Astronomical Society* **388** (2008) 1001 [0803.2217].

[11] A.A. Zdziarski and M. Gierliński, *Radiative Processes, Spectral States and Variability of Black-Hole Binaries*, *Progress of Theoretical Physics Supplement* **155** (2004) 99 [astro-ph/0403683].

[12] R.A. Remillard and J.E. McClintock, *X-Ray Properties of Black-Hole Binaries*, *Annual Review of Astronomy and Astrophysics* **44** (2006) 49 [astro-ph/0606352].

[13] J.D. Schnittman and J.H. Krolik, *X-ray Polarization from Accreting Black Holes: The Thermal State*, *The Astrophysical Journal* **701** (2009) 1175 [0902.3982].

[14] H. Krawczynski, *Tests of General Relativity in the Strong-gravity Regime Based on X-Ray Spectropolarimetric Observations of Black Holes in X-Ray Binaries*, *The Astrophysical Journal* **754** (2012) 133 [1205.7063].

[15] W. Zhang, M. Dovčiak and M. Bursa, *Constraining the Size of the Corona with Fully Relativistic Calculations of Spectra of Extended Coronae. I. The Monte Carlo Radiative Transfer Code*, *The Astrophysical Journal* **875** (2019) 148 [1903.09241].

[16] S. Chandrasekhar, *Radiative transfer*, Dover Publications (1960).

[17] M. Dovčiak, F. Muleri, R.W. Goosmann, V. Karas and G. Matt, *Thermal disc emission from a rotating black hole: X-ray polarization signatures*, *Monthly Notices of the Royal Astronomical Society* **391** (2008) 32 [0809.0418].

[18] L.-X. Li, R. Narayan and J.E. McClintock, *Inferring the Inclination of a Black Hole Accretion Disk from Observations of its Polarized Continuum Radiation*, *The Astrophysical Journal* **691** (2009) 847 [0809.0866].

PoS(MULTIF2023)039

[19] M.C. Weisskopf, P. Soffitta, L. Baldini, B.D. Ramsey, S.L. O'Dell, R.W. Romani et al., *The Imaging X-Ray Polarimetry Explorer (IXPE): Pre-Launch*, *Journal of Astronomical Telescopes, Instruments, and Systems* **8** (2022) 026002 [2112.01269].

[20] H.L. Kestenbaum, G.G. Cohen, K.S. Long, R. Novick, E.H. Silver, M.C. Weisskopf et al., *The graphite crystal X-ray spectrometer on OSO-8.*, *The Astrophysical Journal* **210** (1976) 805.

[21] P. Soffitta, P. Attinà, L. Baldini, M. Barbanera, W.H. Baumgartner, R. Bellazzini et al., *The Imaging X-ray Polarimetry Explorer (IXPE): technical overview III*, in *SPIE*, vol. 11444 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Dec., 2020, DOI.

[22] A. Di Marco, S. Fabiani, F. La Monaca, F. Muleri, J. Rankin, P. Soffitta et al., *Calibration of the IXPE Focal Plane X-Ray Polarimeters to Polarized Radiation*, *The Astrophysical Journal* **164** (2022) 103 [2206.07582].

[23] K.C. Gendreau, Z. Arzoumanian and T. Okajima, *The Neutron star Interior Composition ExploreR (NICER): an Explorer mission of opportunity for soft x-ray timing spectroscopy*, in *Space Telescopes and Instrumentation 2012: Ultraviolet to Gamma Ray*, T. Takahashi, S.S. Murray and J.-W.A. den Herder, eds., vol. 8443 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, p. 844313, Sept., 2012, DOI.

[24] F.A. Harrison, W.W. Craig, F.E. Christensen, C.J. Hailey, W.W. Zhang, S.E. Boggs et al., *The Nuclear Spectroscopic Telescope Array (NuSTAR) High-energy X-Ray Mission*, *The Astrophysical Journal* **770** (2013) 103 [1301.7307].

[25] J.C.A. Miller-Jones, A. Bahramian, J.A. Orosz, I. Mandel, L. Gou, T.J. Maccarone et al., *Cygnus X-1 contains a 21-solar mass black hole—Implications for massive star winds*, *Science* **371** (2021) 1046 [2102.09091].

[26] G. Mastroserio, A. Ingram and M. van der Klis, *An X-ray reverberation mass measurement of Cygnus X-1*, *Monthly Notices of the Royal Astronomical Society* **488** (2019) 348 [1906.08266].

[27] H. Krawczynski, F. Muleri, M. Dovčiak, A. Veledina, N. Rodriguez Cavero, J. Svoboda et al., *Polarized x-rays constrain the disk-jet geometry in the black hole x-ray binary Cygnus X-1*, *Science* **378** (2022) 650 [2206.09972].

[28] J. Poutanen, A. Veledina and A.M. Beloborodov, *Polarized X-Rays from Windy Accretion in Cygnus X-1*, **949** (2023) L10 [2302.11674].

[29] M.J. Reid and J.C.A. Miller-Jones, *On the Distances to the X-Ray Binaries Cygnus X-3 and GRS 1915+105*, *The Astrophysical Journal* **959** (2023) 85 [2309.15027].

[30] M.L. McCollough, C.R. Robinson, S.N. Zhang, B.A. Harmon, R.M. Hjellming, E.B. Waltman et al., *Discovery of Correlated Behavior between the Hard X-Ray and the*

Radio Bands in Cygnus X-3, The Astrophysical Journal **517** (1999) 951 [astro-ph/9810212].

[31] K. Belczynski, T. Bulik, I. Mandel, B.S. Sathyaprakash, A.A. Zdziarski and J. Mikołajewska, *Cyg X-3: A Galactic Double Black Hole or Black-hole-Neutron-star Progenitor*, The Astrophysical Journal **764** (2013) 96 [1209.2658].

[32] A. Veledina, F. Muleri, J. Poutanen, J. Podgorný, M. Dovčiak, F. Capitanio et al., *Astronomical puzzle Cyg X-3 is a hidden Galactic ultraluminous X-ray source*, arXiv e-prints (2023) arXiv:2303.01174 [2303.01174].

[33] F. Marin and F. Tamborra, *Probing the origin of the iron Kα line around stellar and supermassive black holes using X-ray polarimetry*, Advances in Space Research **54** (2014) 1458 [1309.1684].

[34] J.A. Orosz, D. Steeghs, J.E. McClintock, M.A.P. Torres, I. Bochkov, L. Gou et al., *A New Dynamical Model for the Black Hole Binary LMC X-1*, The Astrophysical Journal **697** (2009) 573 [0810.3447].

[35] G. Pietrzyński, D. Graczyk, W. Gieren, I.B. Thompson, B. Pilecki, A. Udalski et al., *An eclipsing-binary distance to the Large Magellanic Cloud accurate to two per cent*, Nature **495** (2013) 76 [1303.2063].

[36] N.E. White and K.O. Mason, *The Structure of Low-Mass X-Ray Binaries*, Space Science Reviews **40** (1985) 167.

[37] J. Podgorný, L. Marra, F. Muleri, N. Rodriguez Cavero, A. Ratheesh, M. Dovčiak et al., *The first X-ray polarimetric observation of the black hole binary LMC X-1*, Monthly Notices of the Royal Astronomical Society (2023) .

[38] W. Forman, C. Jones and H. Tananbaum, *Uhuru observations of a transient X-ray source associated with the globular cluster NGC 6440.*, The Astrophysical Journal Letters **207** (1976) L25.

[39] C. Jones, W. Forman, H. Tananbaum and M.J.L. Turner, *Uhuru and Ariel V observations of 3U 1630-47: a recurrent transient X-ray source.*, The Astrophysical Journal Letters **210** (1976) L9.

[40] E. Kalemci, T.J. Maccarone and J.A. Tomsick, *A Dust-scattering Halo of 4U 1630-47 Observed with Chandra and Swift: New Constraints on the Source Distance*, The Astrophysical Journal **859** (2018) 88 [1804.02909].

[41] A.N. Parmar, L. Stella and N.E. White, *The Evolution of the 1984 Outburst of the Transient X-Ray Source 4U 1630-47*, The Astrophysical Journal **304** (1986) 664.

[42] A. Ratheesh, M. Dovčiak, H. Krawczynski, J. Podgorný, L. Marra, A. Veledina et al., *The high polarisation of the X-rays from the Black Hole X-ray Binary 4U 1630-47 challenges standard thin accretion disc scenario*, arXiv e-prints (2023) arXiv:2304.12752 [2304.12752].

[43] R. Taverna, L. Marra, S. Bianchi, M. Dovčiak, R. Goosmann, F. Marin et al., *Spectral and polarization properties of black hole accretion disc emission: including absorption effects*, *Monthly Notices of the Royal Astronomical Society* **501** (2021) 3393 [2012.06504].

[44] N. Rodriguez Cavero, L. Marra, H. Krawczynski, M. Dovčiak, S. Bianchi, J.F. Steiner et al., *The First X-Ray Polarization Observation of the Black Hole X-Ray Binary 4U 1630-47 in the Steep Power-law State*, *The Astrophysical Journal Letters* **958** (2023) L8 [2305.10630].